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A review of output power smoothing methods for wind energy conversion systems

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A B S T R A C T

Wind energy is inexhaustible renewable. Unlike conventional fossil fuels, wind energy is clean, abundant energy that will be available for future generations. However, wind speed is a highly stochastic component which can deviate very quickly. Output power of the wind energy conversion system (WECS) is proportional to the cube of wind speed, which causes the output power fluctuation of the wind turbine. The power fluctuation causes frequency fluctuation and voltage flicker inside the power grid. In order to reduce the power fluctuation, various approaches have been proposed in the last decades. This article deals with the review of several power smoothing strategies for the WECS. Power smoothing methods of the WECS are primarily separated into two categories such as energy storage based power smoothing method and without energy storage based power smoothing method. The main objectives of this paper are to introduce operating principles for different power smoothing methods. The energy storage based power smoothing method is effective but installation and maintenance costs of a storage device are very high. According to the literatures review, without energy storage based power smoothing method can reduce the cost of the WECS extensively. Various methods have been proposed to generate a smooth output power of the WECS without energy storage devices. Simulation results are compared among the available methods. From the review of simulation results, the kinetic energy of the inertia control method is the highly efficient power smoothing approach.

Contents

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1. Introduction

World primary energy consumption rose by 2.5% in 2011, roughly in line with the 10-year average. In 2011 energy supply by power source was coal 41%, gas 22%, oil 4%, fossil fuels 67%, nuclear 13%, and renewable energies (hydro, solar, wind, geothermal power, biofuels etc.) 20% [1]. Fossil fuels are non-renewable resources because they take millions of years to form, and reserves are being depleted much faster than the new ones are being made [2]. The burning of fossil fuels produces around 21.3 billion tones (21.3 giga-tones) of carbon dioxide (CO_2) per year, but it is estimated that natural procedures can only soak up about half of that amount, so there is a net increase of 10.65 billion tones of atmospheric carbon dioxide per year [3]. Carbon dioxide is one of the greenhouse gases that increases radioactive forcing and contributes to global warming, causing the average surface temperature of the world to rise in response, which the vast majority of climate scientists concur will cause major adverse effects.

The nuclear energy is an unreliable power source and it poses many threats to the people and the environment. These threats include health risks and environmental damage from uranium mining, processing and transport, the risk of nuclear weapons proliferation or sabotage, and the unsolved problem of radioactive nuclear waste [4,5]. Following an earthquake, tsunami, and the failure of cooling systems at Fukushima I Nuclear Power Plant and issues concerning other nuclear facilities in Japan on March 11, 2011, a nuclear emergency was declared. This was the first time a nuclear emergency had been declared in Japan, and 140,000 residents within 20 km (12 mi) of the plant were evacuated [6]. Following the Fukushima Daiichi nuclear disaster, the International Energy Agency halved its estimate of additional nuclear generating capacity to be built by 2035 [7]. In September 2011, German engineering giant Siemens announced that it will withdraw entirely from the nuclear industry, as a response to the Fukushima nuclear disaster in Japan [8]. In the next time, Italy, France and Japan also declared to reduce the nuclear power from their energy consumption pattern.

Due to the problems of fossil fuels and erratic behavior of nuclear power plant, the world has been turning to alternatives of fossil fuels and nuclear energy. Renewable energies have received increasing attention as alternatives of fossil fuels and nuclear energy. Among the several renewable energies, wind energy is the most promising renewable source and it is one of the fastest growing sources of electricity at present [9–20]. According to the half year report 2012 of the World Wind Energy Association (WWEA), the worldwide wind capacity reached 254 GW by the end of June 2012. The total installed wind capacity is expected to reach 273 GW by the end of the year 2012 [21]. Thus, around 2.5% of global electricity consumption has come from wind turbines. Wind is a plentiful source available in the nature, widely distributed, produces no emissions during operation. In the last two decades, the wind power prospective has been studied in many countries worldwide [12,16,19,20,22–27].

Though wind energy is a pollution-free and inexhaustible source, it has some problems. Wind energy is a fluctuating resource which can diverge quickly. As a result, wind power is not constant and can fluctuate significantly since wind power is proportional to the cube of the wind speed. The problems originated by the wind power fluctuations are as follows [28,29]:

- Wind power fluctuations may cause the grid frequency to fluctuate.
- The deviation in wind speed causes the fluctuation of the active power generation and thus the wrapped up reactive power, leading to voltage flicker at the buses of the power grid.
- Frequency fluctuation and voltage flicker deliver a poor power quality and create instability problems in the power system, especially when there are loads sensitive to accept high voltage and frequency variations.

To overcome these problems, various power smoothing methods for the wind energy conversion system (WECS) have been proposed in the last decade. Based on the different power smoothing approaches, the power smoothing methods of the WECS can be divided into two categories-energy storage based power smoothing method and without energy storage based power smoothing method. Several literatures have been proposed to generate a smooth output power of the WECS with energy storage devices. Installation and maintenance costs of these devices are very high. Therefore, the recent trends of the power smoothing methods are considered without energy storage devices, and proposed some approaches to reduce the power smoothing cost of the WECS. Operating principles of different power smoothing methods are reviewed in this paper. Simulation results of an energy storage based power smoothing method are reviewed. Simulation results and comparisons of recently developed without energy storage based power smoothing methods are also discussed in this paper.

2. Wind energy conversion system

Due to the variable wind velocity, the variable speed wind turbine (VSWT) is the most important in the WECS because it can utilize the wind energy proficiently [30]. Doubly fed induction generators (DFIGs) and permanent magnet synchronous generators (PMSGs) based VSWTs are the most popular for the modern wind farm. The system diagram of wind generation system is shown in Fig. 1. The PMSG based WECS is shown in Fig 1(a). The PMSG can omit the gearbox. Hence, it can release all difficulties of the gear box. Wind energy obtained from the wind turbine is sent to the generator. The rotational speed of the PMSG is controlled by a pulse width modulation (PWM) converter. The output power of the PMSG is supplied to the grid through a generator-side converter and a grid side inverter. The system diagram of the DFIG based WECS is shown in Fig. 1(b). The stator of the DFIG is directly connected to the grid, while a back-to-back three-phase voltage source PWM inverter controls the rotor, which, in turn, is connected to the grid on the other side. There are several literatures about modeling and control strategies of the power converters of PMSG and DFIG based WECSs [31–34]. Power smoothing methods can apply any types of VSWTs to generate a smooth output power.

Wind turbine output power, P_w, and wind turbine torque, T_w, are given by the following equations:

$$P_w = \tfrac{1}{2}C_p(\lambda,\beta)\rho\pi R_o^2 V_w^3 \tag{1}$$

$$T_w = \tfrac{1}{2}C_p(\lambda,\beta)\rho\pi R_o^3 V_w^2/\lambda \tag{2}$$

where V_w is the wind speed, ρ is the air density, R_o is the wind turbine blade radius, ω_w is the angular speed of the wind turbine, C_p is the power coefficient, λ is the tip speed ratio, can be defined as $\lambda = (R_o\omega_w)/V_w$, ω_w is the angular speed of the wind turbine and β is the pitch angle. The power coefficient C_p is defined by the following equations.

$$C_p = 0.22\left(\frac{116}{\Gamma} - 0.4\beta - 5\right)\exp^{-(12.5/\Gamma)} \tag{3}$$

$$\Gamma = \frac{1}{\frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}}. \tag{4}$$

The output power characteristics of the wind turbine are depicted in Fig. 2. Here the pitch angle is $\beta = 2^\circ$. From this figure,

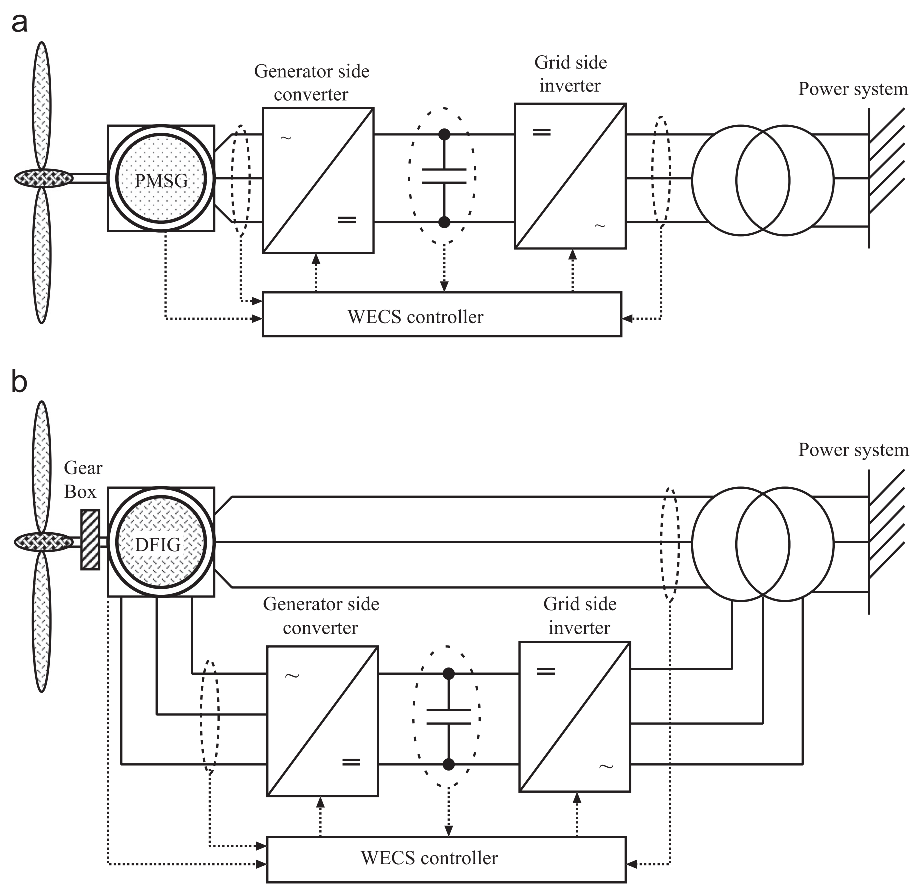

Fig. 1. Wind energy conversion system (a) PMSG based wind turbine, (b) DFIG based wind turbine.

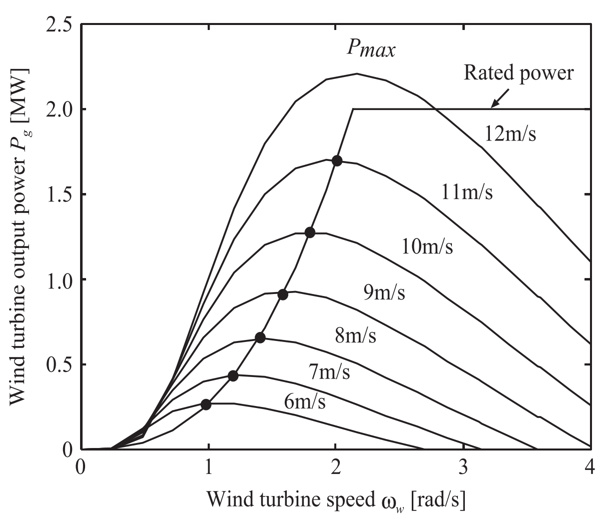

Fig. 2. WECS output power characteristics.

it can be seen that there is a rotational speed, ω_{opt}, dotted by the black circles, for any particular wind speed. ω_{opt} is called the optimum rotational speed and generates the maximum power, P_{max}. In this way, the maximum power point tracking (MPPT) control to each wind speed can increase the power generation for the VSWTs. The value of ω_{opt} is calculated by differentiating C_p with respect to ω_w. Therefore, ω_{opt} is approximated as follows [35]:

$$\omega_w = 0.1874 V_w. \tag{5}$$

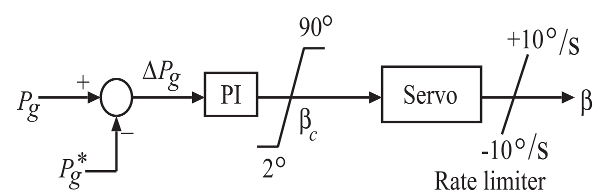

Fig. 3. Pitch angle control system.

Generally, the MPPT control is applied when the wind speed, V_w, is smaller than the rated speed and if V_w is greater than the rated speed, then output power of the generator is controlled by the pitch angle control system [36]. The pitch angle control system of the WECS is shown in Fig. 3. The pitch angle command, β_c, is controlled by the PI controller and the pitch angle selector. In this system, the pitch angle, β, is constant at 2° when the output error of the generator, ΔP_g, is zero. If ΔP_g is positive, then β is increased to reduce the output power of the generator, P_g, and vice versa. P_g is controlled by a hydraulic servo system that drives the blades according to β_c. β_c is limited by a limiter within 2–90°, and the maximum rate of change is $\pm 10°$/s.

3. Power smoothing methods

The major categories of power smoothing methods of the WECS are shown in Fig. 4. There are two foremost types of power smoothing methods such as energy storage based power smoothing methods and without energy storage based power smoothing methods. Ultra capacitor [37–43], battery [44–55], flywheel [56–64], superconducting magnetic energy storage (SMES) [65–72] and fuel

cell [73–75] are popular energy storage devices for the power smoothing of the WECS. Kinetic energy of the inertia control [76–82,86,84–90], pitch angle control [28,36,91–95] and DC-link voltage control [31,96] are proposed in several literatures as a power smoothing technique without energy storage devices.

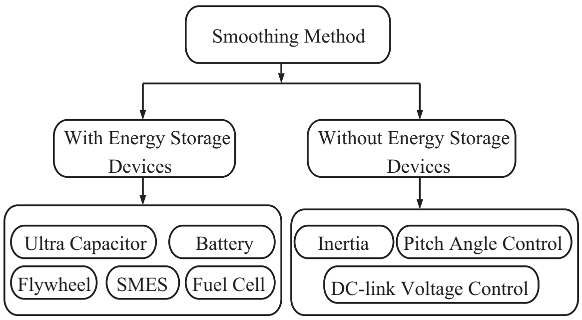

Fig. 4. Power smoothing methods.

3.1. Energy storage based power smoothing methods

In this subsection, power smoothing techniques of the WECS using different energy storage devices are described. The algorithms of the energy storage based power smoothing methods are almost similar to each others. Power smoothing topologies of the ultra capacitor, battery and SMES are identical, fuel cell and flywheel systems are slightly different. The power smoothing methods are described as follows.

3.1.1. Ultra capacitor, battery and SMES based power smoothing

The energy storage system i.e. ultra capacitor, battery or SMES based power smoothing method is shown in Fig. 5(a) and (b). Fig. 5(a) shows that the energy storage is connected to the DC-link

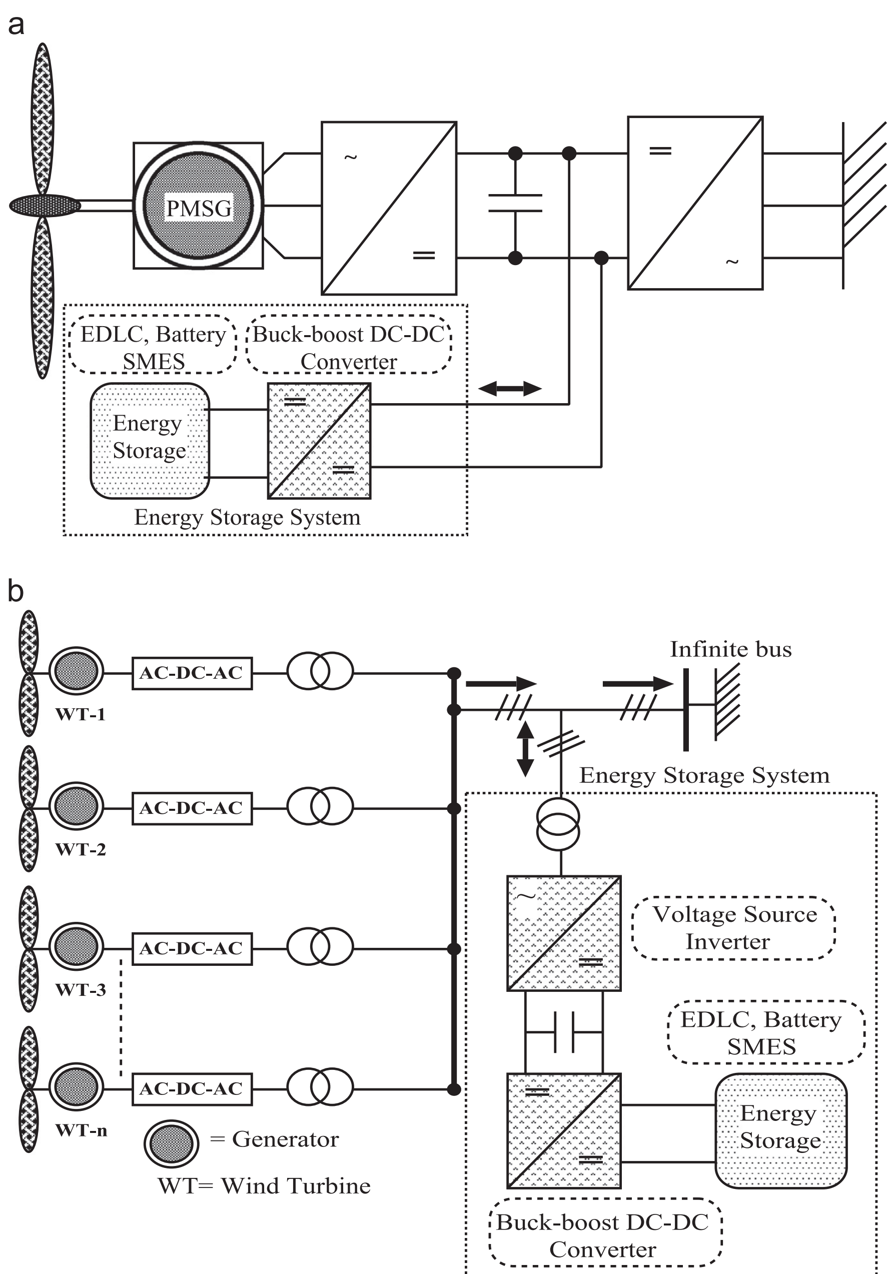

Fig. 5. Energy storage based power smoothing. (a) Energy storage connected to DC link for stand-alone system, (b) energy storage connected to wind farm terminal.

of the frequency converter of the generator. This topology does not require the bi-directional voltage source inverter (VSI) and needs only a buck-boost DC–DC converter to control the real-power which can reduce the system cost. But it is quite appropriate for a stand alone system. If this system is applied to the wind farm which is composed of multiple wind turbines, the energy storage system needs to be installed at each wind turbine and controlled for smoothing the line power. The control strategy of the each energy system will become very complicated. Considering this fact, relatively cost-effective topology for the power smoothing of the wind farm is proposed in Fig. 5(b). From this figure, the energy storage system composed of a step down transformer, a voltage source inverter, a DC-link capacitor and a buck-boost DC–DC converter which is installed at the terminal of the wind farm. When the generated power of the wind turbine is greater than the smooth line power reference signal, the energy storage system charges and vice versa, which is ensured to deliver a smooth power to the power grid.

Ultra capacitor is also known as super capacitor or electric double layer capacitor (EDLC). A super capacitor is an electrochemical capacitor employing conducting polymers as the electrodes [97,98]. A super capacitor enables large power effects per weight having a goal up to 10 kW/kg but a storage capacity around 10 Wh/kg only. The storage time is short or typically up to 30–60 s. A 1 m^3 super capacitor storage may yield in the future a 1–5 MW power pulse and weights 100–500 kg [99]. The price is around 200–600€/kW and 50–150€/Wh but in 5–10 years a price level of 10–15€/Wh is predicted. The most important drawback of super capacitors is their high cost, estimated at five times that of Lead-Acid battery [100].

Batteries are a well-established technology for storage of electricity. The power and capacity that are bound together through the electrode surface are meaning that increasing the power level simultaneously increases the storage capacity. Many types of batteries are now mature technologies. In fact, research activities involving Lead-Acid batteries have been conducted for over 140 years. Notwithstanding, a tremendous effort is being carried out to turn technologies like Nickel–Cadmium (Ni–Cd), Sodium–Sulfur (NaS) and Lithium-Ion (Li-ion) batteries into cost effective options for higher power applications. The capital power costs of the Lead-Acid, Ni–Cd, NaS and Li-ion may vary 50–100 $/kW h, 400–2400 $/kW h, 210–250 $/kW h, and 900–1300 $/kW h, respectively [101,102].

The SMES system is a relatively recent technology. Its operation is based on storing energy in a magnetic field, which is created by a DC current through a large superconducting coil at a cryogenic temperature. The energy stored is calculated as the product of the self inductance of the coil and the square of the current flowing through it [103]. The response time is very short. The SMES technology has been demonstrated but the price is still very high. According to [104], the power injection of a 1 MW/1 kW h SMES can be increased in 200 kW in only 20 ms and the capital power cost may vary between 1000 and 10,000 $/kW.

3.1.2. Fuel cell based power smoothing

The fuel cell based power smoothing method is shown in Fig. 6(a) and (b). Fig. 6(a) shows the fuel cell with electrozer which can generate hydrogen and stored in a tank. The stored hydrogen is used as the fuel for the fuel cell. Fig. 6(b) shows the power smoothing method of the reversible fuel cell. Reversible fuel cells are designed to operate in either water electrolysis mode or power generation mode. For a wind-hydrogen system that stores hydrogen energy for later conversion back to electricity, reversible fuel cells may offer cost benefits compared to separate units for hydrogen production and power generation. Reversing the electrochemical reaction within the same cell is challenging because of the technical problems of optimizing the electrode structure and composition. According to Mitlitsky et al. [105] reversible proton exchange membrane (PEM) fuel cells with appropriate catalysts have been demonstrated to have high cycle life and equally good performance as individual electrolyzers and fuel cells. The fuel cell based power smoothing algorithm is similar as the other energy storage devices (e.g. battery, EDLC). When the fuel cell is used for power smoothing to a wind farm, it is installed to the terminal of the wind farm as similar as Fig. 5(b). The installed cost of a fuel cell system depends on the type of fuel cell system selected, configuration, and size. Cost information can be obtained by contacting a fuel cell manufacturer. Installation costs of a fuel cell system can range from $5,000/kW to $10,000/kW.

3.1.3. Flywheel based power smoothing

In a flywheel, the storage capacity is based on the kinetic energy of a rotating disc which depends on the square of the rotational speed. A mass rotates on two magnetic bearings in order to decrease friction at high speed, coupled with an electric machine. Energy is transferred to the flywheel when the machine operates as a motor (the flywheel accelerates), charging the energy storage device. The FESS is discharged when the electric machine regenerates through the drive (slowing the flywheel). The FESS stores energy when the wind turbine generates more power, and discharges energy when wind turbine delivers less power. As a result, the wind turbine generates a smooth output power. A stand-alone FESS based power smoothing system is shown in Fig. 7(a). From this figure, the flywheel is connected to the wind turbine system through a motor and a voltage source inverter. Fig. 7(b) shows the power smoothing method for the wind farm by using the FESS. The FESS is connected to the wind farm terminal through a coupling transformer, a voltage source converter, a voltage source inverter and a motor drive. In fact, the energy stored by the flywheel is dependent on the square of the rotating speed and its inertia. In general, flywheels can be classified as low speed or high speed devices. A FESS presents suitable features regarding high efficiency (around 90% at rated power), long cycling life, wide operating temperature range, freedom from depth-of-discharge effects, higher power and higher energy density [106,107]. The investment cost would be around 150–250€/kW.

The different characteristics of the energy storage devices are summarized in the tables of Refs. [101,102].

3.2. Power smoothing methods without energy storage devices

Power smoothing methods by using the energy storage devices are effective, but they impose a significant additional cost to the system. Therefore, the power smoothing methods without energy storage devices can reduce the system cost extensively. In this section, different power smoothing methods without energy storage devices are described.

3.2.1. Power smoothing by controlling the kinetic energy of the inertia

The basic idea is to use the energy in rotor inertia to smooth the output power of the WECS. Since the kinetic energy of the wind turbine inertia is significant, it can be utilized to generate a smooth output power as an energy storage device. The concept behind this method depends on two events [79,81,83]:

- Increase in wind turbine kinetic energy due to the acceleration of the turbine rotational speed when wind speed rapidly increases.

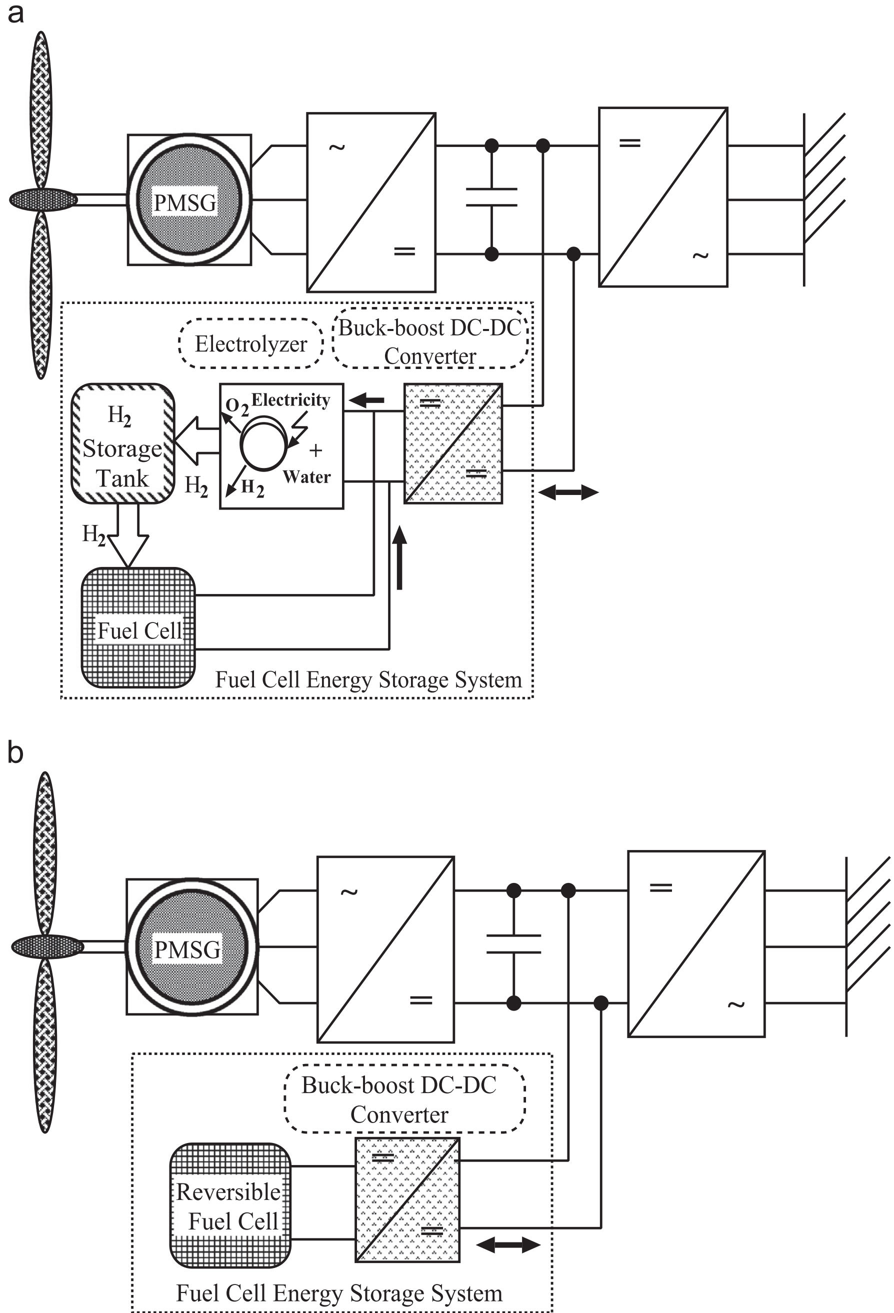

Fig. 6. Fuel cell based power smoothing. (a) Fuel cell connected to DC link for stand-alone system, (b) reversible fuel cell connected to DC link for stand-alone system.

- A discharge of wind turbine kinetic energy due to a decline in the wind turbine rotational speed when the wind velocity drops.

The maximum output power of the wind turbine P_{max} is calculated as

$$P_{max} = T_w \omega_{opt} \tag{6}$$

The average value of the maximum wind turbine output power is calculated as

$$P^* = \frac{1}{T}\int_{t-T}^{t} P_{max}\, dt \tag{7}$$

where t denotes the present time and T is the averaging time. Then, the power difference ΔP between the maximum output power and the average value of the maximum output power is determined. The ΔP gives the storing and restoring power in inertia of the wind turbine. Therefore, the $\int \Delta P$ gives the wind turbine storing and restoring energy. Wind turbine kinetic energy, E, is determined as

$$E = \tfrac{1}{2} J_{eq} \omega_g^2 \tag{8}$$

The wind turbine rotational speed command, ω_g^*, is determined from the kinetic energy command, E^* (the sum of $\int \Delta P$ and E), as [81–83]

$$\omega_g^* = \sqrt{\frac{2E^*}{J_{eq}}}. \tag{9}$$

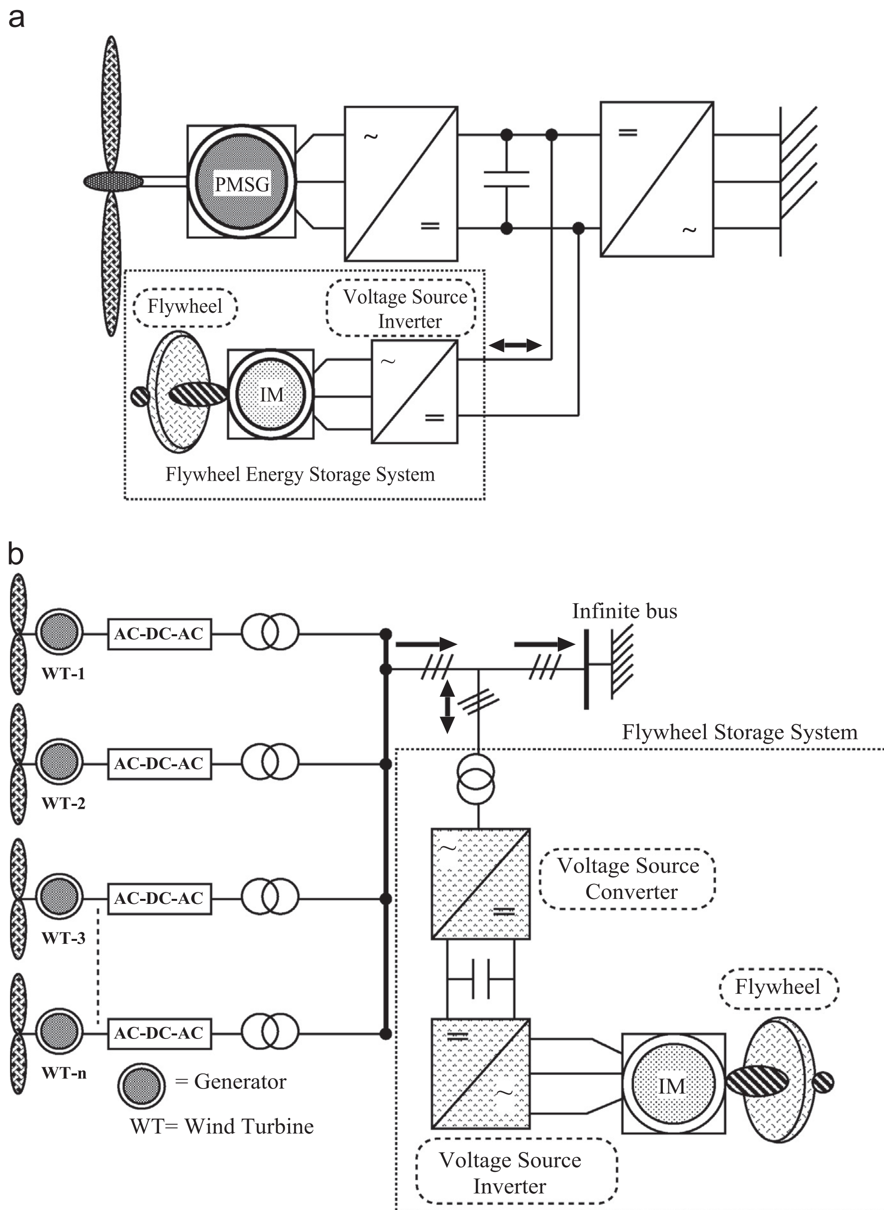

Fig. 7. Flywheel based power smoothing. (a) Flywheel connected to DC link for stand-alone system, (b) flywheel connected to wind farm terminal.

Finally, the generator electrical reference speed ω_e^* for this method is determined from the number of pole pairs p, as

$$\omega_e^* = \omega_g^* p \tag{10}$$

The generator electrical reference speed ω_e^* helps to provide a smooth output power of the WECS.

3.2.2. *Power smoothing by pitch angle control system*

Pitch angle control has been one of the most common methods for smoothing at output power fluctuations during below rated wind incidents. A fuzzy logic pitch angle controller is included for smoothing wind power fluctuations during below rated wind incidents beside traditional power regulations during above rated wind incidents [28,29,36]. The power smoothing method can generate a smooth output power of all the operating regions. Pitch angle controller with the fuzzy logic system (FLS) has advantageous in a numerous ways. Wind turbine system is highly non-linear with many uncertain factors like meteorological conditions and continuously varying AC system loads. It also contains some unknown ambiguous dynamics which make accurate dynamic modeling of a wind turbine system difficult or even impossible [108]. However, the rules of the FLS possess expert adaptability and learning capability to reason precisely with imprecise, uncertain, incomplete and non-linear data from a wind turbine system [108,109]. Moreover, It is cheap, reliable, robust and energy efficient.

Fig. 8 shows the fuzzy controller based pitch angle system with two combined FLS (i.e. FLS-A and FLS-B) to generate a smooth output power. Design strategies of FLS-A and FLS-B are described below [28].

When the wind turbine operates during the wind incident above the rated value, the generator rotor speed exceeds the control speed value. In this mode of operation, the controller has got nothing to do regarding power fluctuation minimization, because currents of the generator are the maximum rating, which

ensures the rated output power of the generator. The FLS-A has been incorporated the command pitch angle controller (β_{cA}), which is only active in this mode of operation.

On the other hand, when the wind turbine operates during the wind incident below the rated value, there is no generation of pitch angle. Any variation in wind speed can cause high fluctuations in wind power. To smooth the fluctuating wind power, the FLS-B has incorporated the command pitch angle (β_{cB}). The power reference ($P_{g_{ref}}$), power command ($P_{g_{com}}$), power stage (PS) target value ($P_{g_{tar}}$), fuzzy membership functions and rules are given in detail in Ref. [28].

3.2.3. Power smoothing by controlling the DC-link voltage

The grid-side inverter aims to control the DC-link voltage, V_{dc}, and the grid voltage, V_t of the WECS [31,87–89]. The d-axis current controls the DC-link voltage, while the q-axis current controls the grid voltage. To generate a smooth output power, this method controls the DC-link voltage of the DC-link capacitor. The DC-link voltage command, V_{dc}^*, is calculated by adding the rated DC-link voltage, to a simple smoothing index, ΔV_{dc}. Here, the smoothing index is based on the output power fluctuations of the generator. If the smoothed output power is P_c, then the output power of the generator-side converter is P_g, and the charge/discharge power of the DC-link capacitor is ΔP_{dc}. ΔP_{dc} is expressed by [31,96]

$$\Delta P_{dc} = P_c^* - P_g \tag{11}$$

where, the smoothing command, P_c^*, is determined by filtering the P_g through a low-pass filter which has the time constant of 1 s. Using the DC-link current, I_{dc}, the smoothing index, ΔV_{dc}, is determined by

$$\Delta V_{dc} = \frac{\Delta P_{dc}}{I_{dc}}. \tag{12}$$

The control system of the DC-link voltage control system is shown in Fig. 9. The control system provides a variable V_{dc}^* instead of the constant V_{dc}^*. To prevent the deterioration of the DC-link capacitor, the high frequency components of P_g are eliminated by using a low-pass filter. The time constant is set to 0.4 s by trial and error. To prevent over-voltage, the smoothing index, ΔV_{dc}, is limited within ± 1 kV, i.e. the controllable region of the DC-link voltage is about 0.86–1.14 pu. The output of the PI controller is used an inner-loop and is limited to ± 3 kA to prevent over-current. The output of the PI controller is the d-axis current commanded i_{2d}^*, and the error of the d-axis current (difference between i_{2d}^* and actual i_{2d}) is an input of a PI controller. Finally, the output of the controller system is the d-axis voltage command V_{2d}^*.

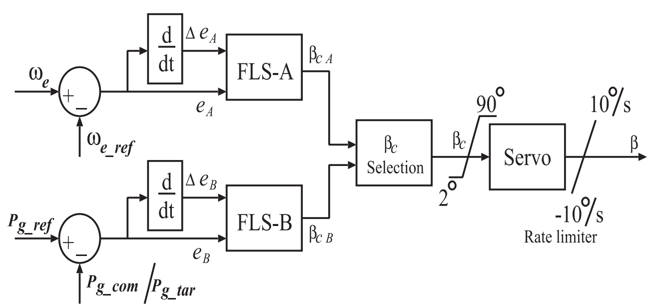

Fig. 8. Power smoothing scheme of the fuzzy logic pitch angle controller [28].

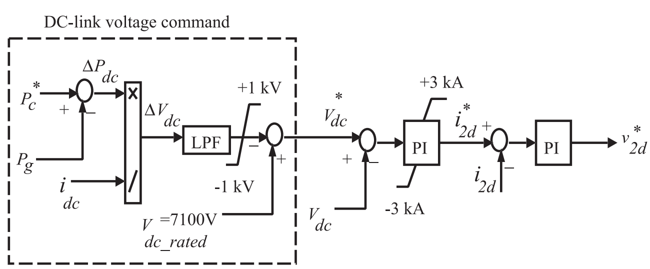

Fig. 9. DC-link voltage control system for power smoothing [31].

4. Review results and discussion

Each power smoothing method holds some advantages and disadvantages. The energy storage based methods can provide an

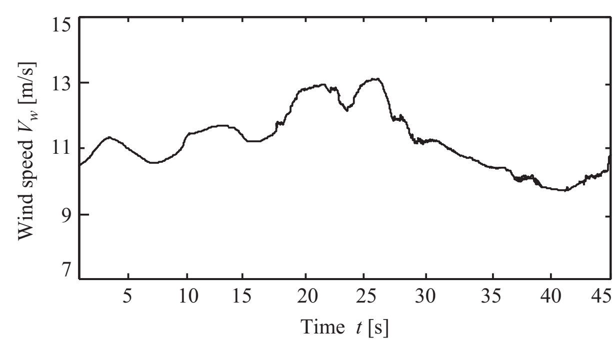

Fig. 11. Wind speed.

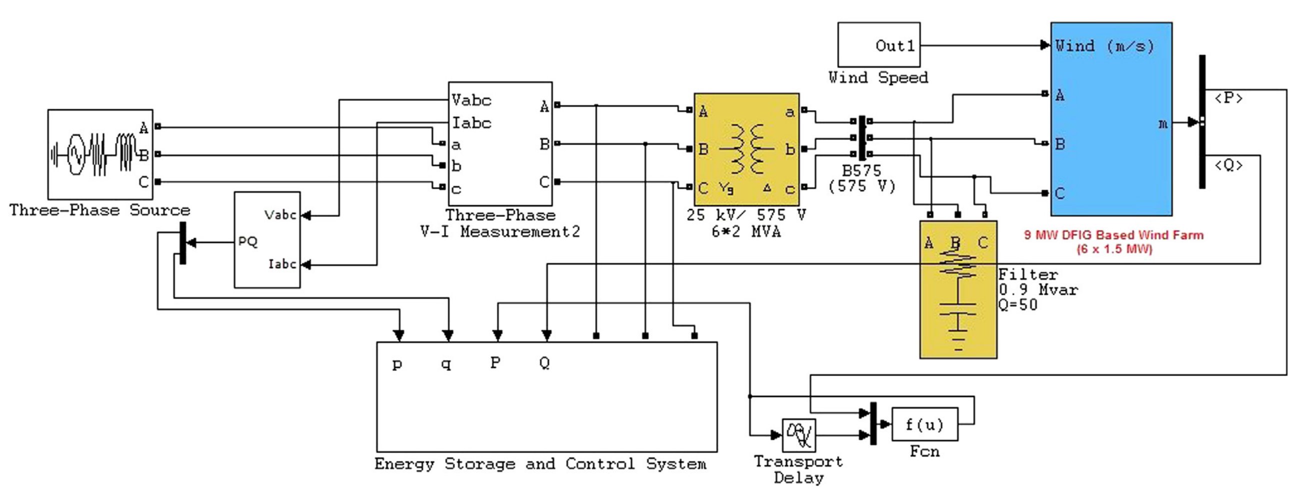

Fig. 10. Simulation system model with energy storage system.

efficient power smoothing but require an additional cost for the system. The diagram of the simulation system with an energy storage device is shown in Fig. 10. The wind farm consists of six DFIG based wind turbines and parameters of each wind turbine are given in Appendix A. The line power is smoothed by the energy storage system. In this simulation, the energy storage system is considered as the EDLC and control system is given in [38,41]. Fig. 11 shows the wind velocity for the wind farm. Different powers of the wind farm is shown in Fig. 12. From this figure, the output power of the wind farm is fluctuated according to the wind speed. The reference line power is generated from exponential moving average (EMA) of the output power of the wind farm [41]. The response of the line power is similar as the reference power and delivers a smooth power to the power grid (in Fig. 12). Fig. 13 shows the output power of the energy storage system. When the reference line power (in Fig. 12) is higher than the output power of the wind farm, the EDLC will be discharged and vice versa. In Fig. 13, the negative values represent the discharge of the EDLC, and the positive values represent the charge of the EDLC. From Figs. 12 and 13, the EDLC stores energy when the generated power of the wind farm is higher than the reference power, and the EDLC restores energy when the generated power of the wind farm is lower than the reference power. As a result, the line power of the wind farm becomes smooth. All the energy storage devices show the similar behaviors for the power smoothing of the WECS.

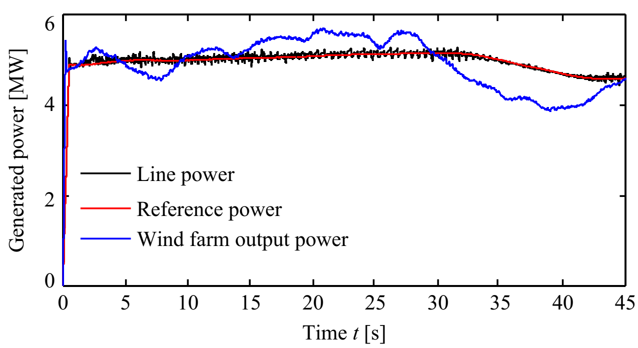

Fig. 12. Different powers of wind farm.

The simulation system diagram without energy storage system is shown in Fig. 14. The power smoothing methods and the MPPT control method are applied in PMSG based wind turbine system. Simulation parameters are given in [31]. Simulation results are compared among the four different methods. Each power smoothing method is compared with the MPPT control method to ensure the power smoothing efficiency. A wind speed profile is shown in Fig. 15. Fig. 16 illustrates the generated power (P_g) of the wind turbine. From this figure, each power smoothing method can generate a smooth output power as compared with the MPPT control method. Pitch angle control method and DC-link voltage control method can deliver a smooth output power, but these

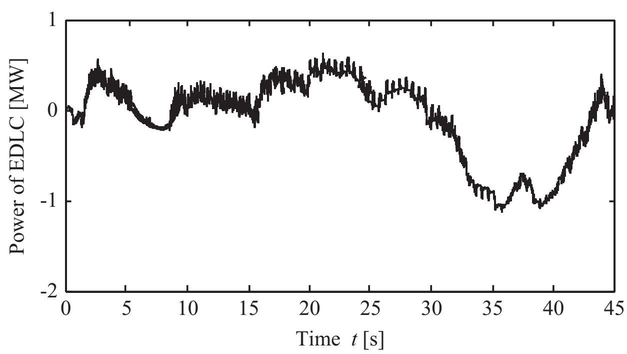

Fig. 13. EDLC bank power.

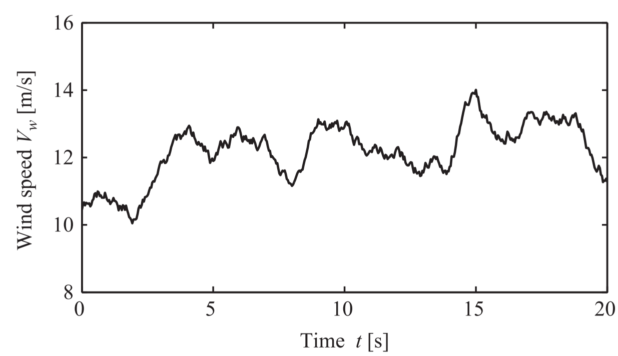

Fig. 15. Wind speed.

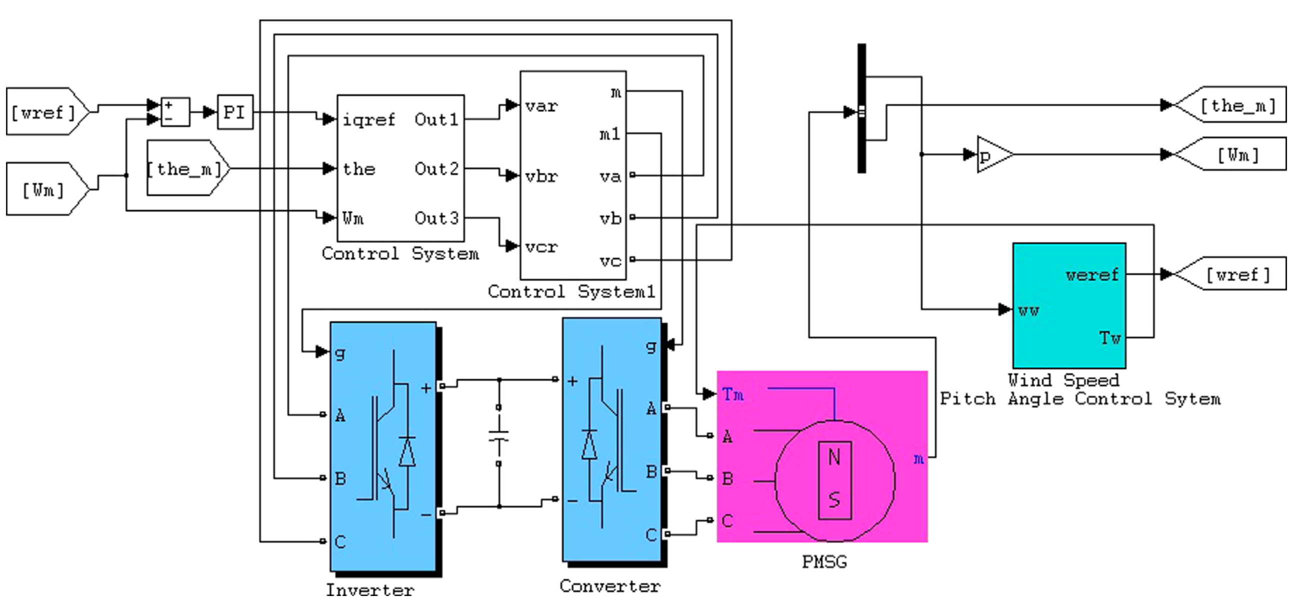

Fig. 14. Simulation system model without energy storage.

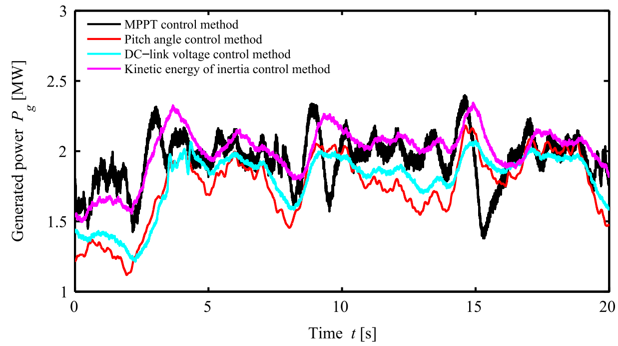

Fig. 16. Generated power of different approaches.

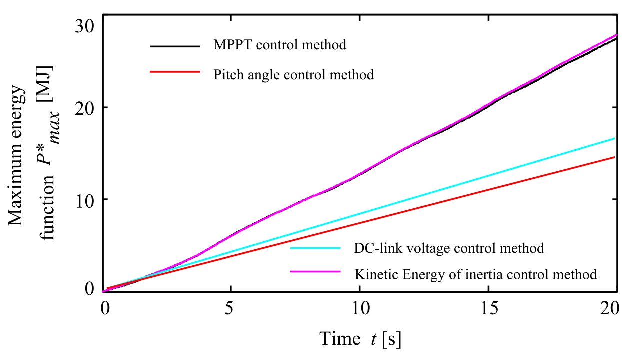

Fig. 17. Maximum energy function of different approaches.

methods reduce the output power extensively as compared with the MPPT control method. Therefore, these methods are not able to generate an efficient power smoothing of the WECS. For the pitch angle control method, the pitch angle should activate all the operating region (e.g. above the rated wind speed and below the rated wind speed) for power smoothing [28,29,36]. Therefore, it increases the blade stress significant of the wind turbine. The DC-link voltage control method generates a variable DC-link voltage [31,96]. It creates a pressure on the DC-link capacitor which may shorten the life time of the capacitor. The kinetic energy of the inertia control method can generate a smooth output which also ensures the similar power as the MPPT control method (in Fig. 16).

Efficiency evaluation of the output power smoothing is represented by the maximum energy function P^*_{max} and the smoothing function P^*_{level} as [28,36]

$$^*P_{max} = \int_0^t P_g(t)\,dt \quad (13)$$

$$^*P_{level} = \int_0^t \left| \frac{dP_g(t)}{dt} \right| dt. \quad (14)$$

If $^*P_{max}$ is large, the output power efficiency of the WECS will be large. From Fig. 17, the maximum energy function of the MPPT control method is similar as the kinetic energy of the inertia based power smoothing method. It reflects that there is no energy loss for this power smoothing method. The maximum energy function of pitch angle control method and DC-link voltage control method (in Fig. 17) is smaller than the kinetic energy of the inertia control method as well as the MPPT control method. So, these two methods are inefficient because these decrease the energy to generate a smooth output power of the WECS. From this figure, it can be summarized that the kinetic energy of the inertia control method can generate an efficient power smoothing of the WECS as compared with the DC-link voltage control method and pitch angle control method. On the other hand, if the smoothing function $^*P_{level}$ is small, the output power fluctuation will be small,

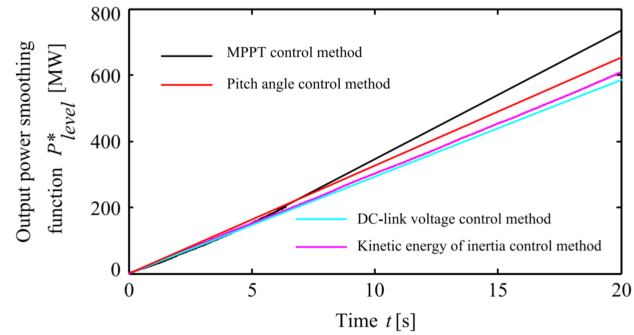

Fig. 18. Power Smoothing Function of different approaches.

which is the indication of a good performance in the power smoothing of the WECS. Fig. 18 shows that the smoothing function drops by the power smoothing methods as compared with the MPPT control method. Therefore, it ensures a good smoothing performance by the power smoothing methods. The power smoothing performance of the DC-link voltage control method and the kinetic energy of the inertia control method is almost similar. The smoothing performance of the pitch angle control method is worse than the DC-link voltage control method and kinetic energy of the inertia control method. Again, all power smoothing methods can generate a smooth output power as compared with the MPPT control method.

5. Conclusion

This paper reviewed and discussed various power smoothing methods for the WECS which are still an active research area of the WECS. Due to the excessive cost of the energy storage devices, researchers have prompted to show interest in the without energy storage based power smoothing systems. Simulation results of the energy storage based power smoothing method are shown in this paper. The energy storage device can store energy and it can also restore energy to generate a smooth output power. A comparison of without energy storage based power smoothing methods is also shown in this paper. Available methods are compared with the MPPT control method. The kinetic energy of the inertia control method is superior than DC-link voltage control method and pitch angle control method. This method can deliver the similar power as the MPPT control method. It can also able to improve the power smoothing performance.

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Appendix A

Parameters of a DFIG generator: rated power $P_{g_{rated}} = 1.5$ MW, pair of poles $p=3$, stator resistance $R_s=0.00706$ pu, stator inductance $L_s=0.171$ pu, rotor resistance $R_r=0.005$ pu, rotor inductance $L_r=0.156$ pu, mutual inductance $L_m=2.9$ pu, inertia constant $H=5.05$ pu, friction coefficient $F=0.01$ pu, rated DC-link voltage V_{dc} rated$=575$ V, DC-link capacitor $C=0.06$ F.

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